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The impact of instrument choice on investment in abatement technologies: a case study of tax versus trade incentives for CCS and Biomass for electricity

EPRG Working Paper 1004

Cambridge Working Paper in Economics 1012

Tim Laing and Michael Grubb

Abstract

There has been a wide discussion on the different properties between carbon taxes, cap-and-trade schemes and hybrid instruments such as cap-and-trade schemes with price floors and ceilings. There has been less discussion on the incentives to investment that each of these instruments may provide. We build a three-period model to investigate the incentives offered to a large firm with diversified abatement options from such instruments when facing a choice between investing in low-carbon technologies with potential learning benefits. We parameterise our model for a system similar to the EUETS and for two sample technologies, biomass for electricity and coal with carbon capture and storage. For both technologies we find that cap-and-trade schemes generate greater mean returns to such an investment than taxes, but with a wider distribution. We find that introducing price floors increase such mean returns while reducing the distribution, while ceilings further reduce the distribution, but also the mean and thus the overall incentives they offer will depend on the risk preference of the firm and scale of investment in relation to overall compliance costs.

Keywords Carbon Markets, Investment, Cap-and-trade, CCS, Biomass

Contact tjl40@cam.ac.uk
Publication February 2010
Financial Support ESRC, TSEC 2

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The impact of instrument choice on investment in new abatement technologies: a case study of tax versus trade incentives for CCS and Biomass for electricity

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1. Introduction

The greenhouse gases reductions that will be necessary to limit the damages from climate change are likely to require widespread innovation in, and deployment of, new technologies. This will require both large additional investments, and also a shift from investment in carbon polluting technologies. Placing a price on carbon emissions, either through a tax or through cap-and-trade schemes helps to incentivise such technologies. This is especially crucial for both end-of-the-pipe technologies such as Carbon Capture and Sequestration (CCS) for which the only motivation to implement is to reduce carbon emissions – and also technologies such as biomass for power which have potentially wider benefits (such as energy security), but for which carbon policies can provide significant incentives nonetheless. Providing clear and sufficient incentives for both types of technologies is one of the multiple aims of carbon mitigation policies.

The levels of investment that instruments to address carbon abatement drive may be crucial in meeting the long-term challenge of mitigation. CCS is predicted to play a major role in both the electricity and industrial sector in the decades to come (for example see Anandarajah et al 2009), yet so far there has been limited private sector investment. Biomass energy utilisation is a technology that is attractive for its carbon neutrality and can potentially meet a wide variety of energy needs including electricity supply. Doubts remain over the stability of supply chains, and development in this area from learning-by-doing is crucial for a wider deployment of the technology.

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The returns that an investment in such technologies may yield to investors depend on the exact nature of the carbon policy implemented by governments. Our work compares the differing firm-level returns to investment that these different instruments yield.

Under certainty and complete information, there is equivalence between taxation and quantity controls for controlling pollution. For many situations including climate change, however, there is neither certainty nor complete information. Uncertainties persist over both the costs of controlling emissions and the damages emanating from these emissions, as well as the associated nature of, and the response to, future policies; and all of these compounds the asymmetric information that exists between firms and regulators. An example of the range of uncertainty over damages or the social cost of carbon can be seen in Figure 1. Estimates for 2050, even for this specific model vary by a factor of more than twenty.

The uncertainties can be grouped into two basic areas. The first concerns the likely 'cost of carbon' that firms will face. Uncertainties over the impact of Greenhouse Gas (GHG) emissions on the climate compound with geographical and economic factors to create large uncertainties over the level of damages, resulting from a certain level of GHG emissions. In addition there is major policy uncertainty over both the choice and level of instruments put in place to address carbon abatement their economic implications. It is through this channel of policy that such uncertainties manifest themselves to firms.

The second area of uncertainty relates to that arising around possible mitigation technologies. Uncertainty and asymmetric information exists over many facets of such technologies. As many of the technologies that are likely to be required are new and relatively sparsely deployed there are large uncertainties over the pace and scale of feasible deployment of these technologies, along with wide ranges of estimates over both capital and operating costs. These uncertainties are likely to be larger for regulators than for firms due to asymmetric information between the parties.

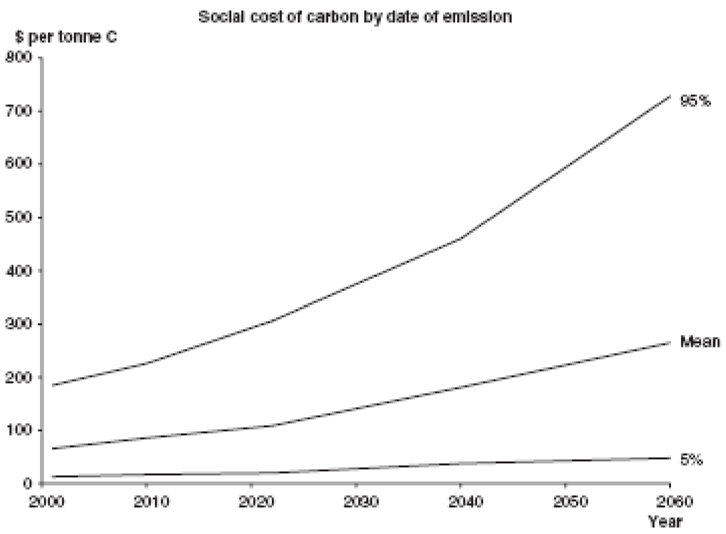

Figure 2.3. Social cost of carbon over time for $\delta = 1.5\%$ and $\nu = 1$

Figure 1: Social cost of carbon over time, Hope and Newberry (2008)

Our aim is to investigate the impact that the choice of instruments has on firm-level incentives to invest in a new technology in a world with uncertainties such as those described above. It is well established that carbon pricing can play a key role in creating incentives (see for example Stern 2006, and earlier work by Pigou 1920 and Coase 1960). However there is a long standing debate about the relative merits of doing so through a direct tax, or through a system that caps quantities and establishes a market in emission allowances (cap-and-trade).

The debate has been reflected in policy development. In 1990 the US established a cap-and-trade scheme for regulating SO_2 emissions, and during the subsequent decade the EU attempted to introduce a carbon tax for regulating greenhouse gas emissions. The EU's carbon tax eventually failed after widespread opposition from industry and several member states (Anderson et al 1996, Bergesen et al 1994) and around 2000 EU efforts switched to considering a cap-and-trade scheme for carbon dioxide, which came into force in 2005. However, volatility in the price (coupled with surplus allocations) - and opposition in the US to plans for a greenhouse gas cap-and-trade scheme there - have renewed some political debate about the choice. The experience points to potential political economy advantages to a cap-and-trade approach, but this paper focuses upon economic incentives.

We build on existing strands of work that model the choice between taxes and quantity constraints when viewed from a societal perspective and work that compares the impact that the choice of instruments has on investment incentives in a world without uncertainty.

We build a simple, stylised, multi-period model to examine the returns that a firm can obtain from investing in a new abatement technology. We explore its behaviour and implications using parameters for two technologies, Biomass for electricity and CCS, and for a trading system similar to the EU's Emission Trading Scheme (EUETS) to gain greater insights relevant to the climate change problem.

Our model generates distributions of the returns over and above investment for both technologies against a reference investment. We obtain distributions for taxes (under different methods of formation), cap-and-trade schemes and cap-and-trade schemes with price floors and ceilings. We find that the distribution of returns vary between these instruments, with cap-and-trade schemes generating greater mean returns than taxes in two out of three cases, but with a much wider distribution of returns. The introduction of floors can increase average returns and reduce the distribution, while ceilings further reduce the distribution but at the cost of average returns.

Our work adds to the literature in a number of areas, by adding uncertainty into the discussion of investment incentives from different instruments for pollution, by focusing previous work comparing instruments under uncertainty on the incentives they offer to firms, by extending work into a multi-period world with a programme of investment and by applying such work to potentially important technologies.

In Section 2 we discuss some of the existing literature in this area. Section 3 outlines the theoretical model that we construct. In Section 4 we describe the data we use for calibration of the model. Section 5 outlines our results from the calibrated model. We discuss implications for policy in Section 6 and conclude in Section 7.

2. Literature

Investment under uncertainty has been studied extensively in the literature (Dixit and Pindyck 1994, Cabelero 1991). Baker and Adu-Bonnah (2008) applied this literature to climate change by analysing how the level of socially optimal R&D investment changes with the risk profile of the R&D program and uncertainty about climate damages. They examine two types of technical change, differentiated by their effect on the abatement cost function: one which they term 'alternative R&D', which shifts the abatement cost function down by a fixed percentage; and the second which they term 'conventional technology', which reduces the emissions-output ratio and reduces everywhere (weakly) the cost of abatement, whilst leaving the full cost of abatement unchanged. The latter of these changes has the affect of reducing the marginal cost in some areas of the curve, whilst increasing it at higher levels of abatement, implying a pivot of the affine marginal abatement curve. In the first case of technical change they find that optimal investment is higher in risky R&D than in non-risky, while in the latter the level of investment in R&D depends more on the level of damages from climate change than the risk profile of the R&D.

A number of authors have undertaken work which rank different policies such as taxes, auctioned and free permits and performance standards for pollution abatement according to the firm level incentives to undertake investment in abatement technologies that they yield (Milliman and Price 1986, Jung, Krutilla and Boyd 1996, Montero 2000, Requate and Unold 2001). This group of work yields different rankings of instruments depending on assumptions over the type of firm or industry undertaking investment, the stage in the innovation process and the market structure of output and permit markets. One common feature among this literature is the absence of uncertainty in its analysis.

This omission of uncertainty is a major limiting factor in applying the literature's conclusions to problems such as climate change. A second strand of literature has compared the properties of instruments such as taxes and quantity constraints, both traded and non-traded in the presence of uncertainty. This literature uses both analytical and parameterised models that examine the differing properties of instruments for pollution control from a broader perspective, focusing on overall societal benefits rather than firm-level incentives to investment.

Weitzman (1974) investigated the choice between taxes and quantities in the presence of uncertainty and found that the comparative advantage of prices over quantities depends on the relative slopes of the marginal cost and benefit curves.

Weitzman's work is not climate-specific, although it has been used to reach conclusions regarding the issue. The social cost of carbon, (the marginal benefit of abatement), can be assumed to have a smaller slope (at least in terms of near-time abatement) than marginal abatement costs, assuming climate change to be a fundamentally stock problem. Damages are linked to aggregate GHG concentrations, thus one tonne of GHG emitted has similar costs as any other, implying a relatively flat social cost of carbon curve. Abatement costs, on the other hand, rise sharply as abatement increases, as there are a number of relatively cheap mitigation opportunities available (energy efficiency for example), but once these opportunities have been utilised costs rise sharply. As argued by several subsequent authors Weitzman's analysis, would, from this perspective, favour the use of carbon taxes over quantity constraints. Figure 2a shows an example of the Weitzman analysis where both the abatement costs and the social costs are subject to a certain degree of uncertainty. In the diagram taxes and quantity constraints are determined as per the expected levels of marginal abatement costs (MAC_E) and social costs of carbon (with taxes at T_E, and quantity constraints at Q_E). If however marginal abatement costs are actually higher than expected (MAC_{Real}, where Q_{Real} represents the efficient level of abatement in such a case), the efficiency loss from taxes is far smaller than that from permit schemes, thus favouring the use of taxes.

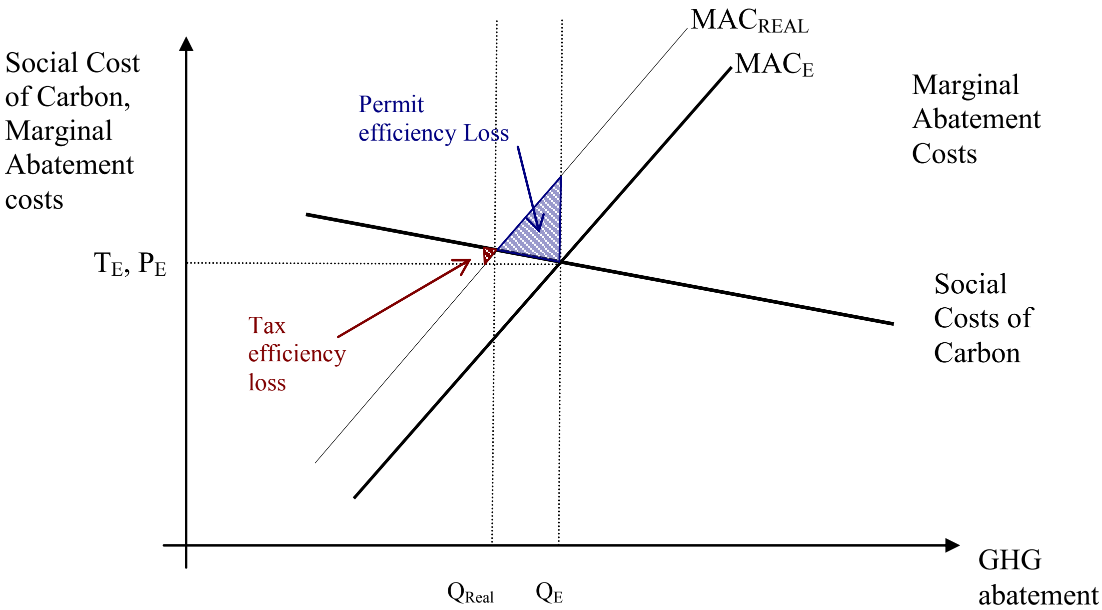

Figure 2a: Stylised representation of the instrument choice problem) stylised (Source: Dietz 2006)

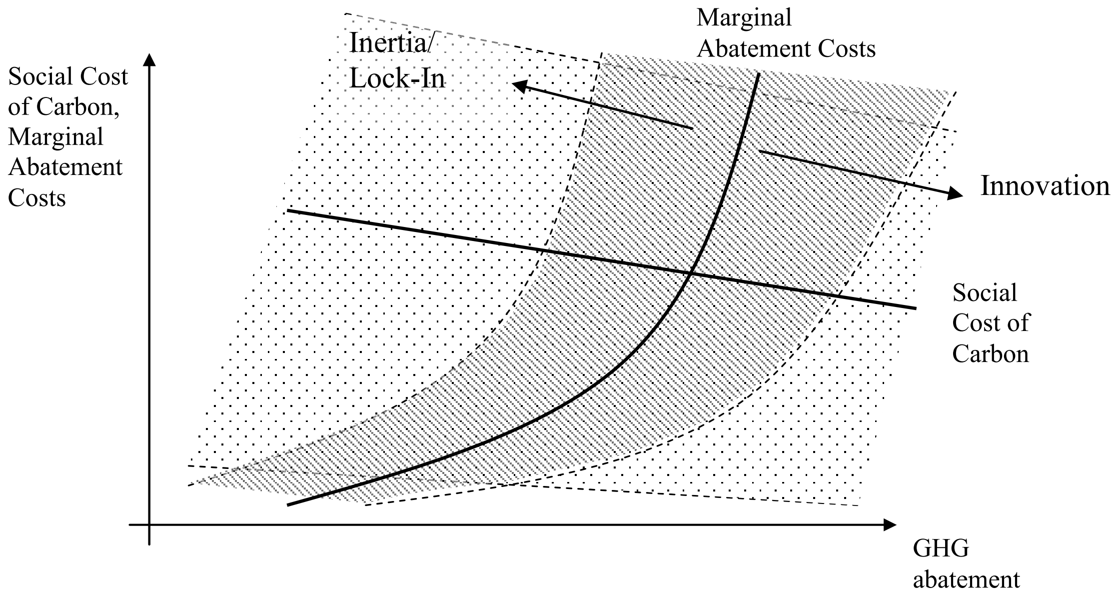

Figure 2b: Representation of the climate problem reflecting further details

In reality the climate problem is more complex than the stylised representation in Figure 2a. Figure 2b illustrates a more accurate portrayal of the climate problem. The scale of uncertainty over damages is vast, even larger than that portrayed here and certainly greater than that surrounding marginal abatement costs. Marginal abatement costs curves are also highly convex, thus their slope depends on the scale of abatement being considered. The 'stock' nature of climate change, along with issues of inertia, and long-term investments that are a large part of the energy system, means that the problem must be seen in a dynamic context; such features, along with the impact of innovation can both shift and change the slope of the marginal abatement curve. Taking into account these elements means that the issue of the optimal choice of instrument is still unresolved.

Post-Weitzman there has been a number of papers extending his work in some of these highlighted areas and extending his analysis to the climate problem. Stavins (1996) extended the work by examining the case when cost and benefit uncertainties are correlated and found that positive correlations tend to favour quantity instruments while negative correlations favour price instruments. For plausible values of parameters they find that quantity instruments may be favoured over price instruments.

Hoel and Karp (2001) compare taxes and quotas when regulators have asymmetric info about the slope of firms' abatement costs with damages arising from a stock pollutant. Using an integrated climate-economy model without endogenous technology change Pizer (2002) found that taxes are more efficient than permits by a factor of five to one, though a hybrid policy allows the same efficiency while maintaining the flexibility to distribute the rents. Newell and Pizer (2003) extend Weitzman's analysis to stock externalities. As in Weitzman they find that relative slopes are the key determinants of the efficiency of the instruments, however they find that further elements are also important including correlation of cost shocks over time, discounting, stock decay and the rate of benefits growth.

Phillibert (2008) uses an Abatement Costs Temperature Changes (ACTC) model to conduct a quantitative assessment of price caps and floors, concluding that hybrid instruments may be better than any single instrument. They calibrate the model using estimates for greenhouse gases and find that taxes produce greater overall returns than quotas when there is multiplicative uncertainty.

Weber and Neuhoff (2008) examine the effects of firm-level innovation in carbon-abatement technologies on optimal cap-and-trade schemes with and without price controls through an analytical model. They find that an increase in innovation effectiveness lowers optimal emissions caps and relaxes price controls. Innovation makes the optimal instrument more similar to a cap; it widens the spread of the optimal floor and ceiling.

Although the area of suitable instrument choice for mitigation of GHG emissions has been widely studied, there is little work in the specific area of the firm-level investment incentives in a world with uncertainty. Our work sits between the strand of literature that focuses on investment incentives to firms of pollution abatement instruments, and the strand focusing on the overall choice of instruments for climate change. We build on the literature examining incentives by offering an alternative modelling of the impact of a new technology on the abatement curve, building in uncertainties and parameterising for relevant technologies. We draw lessons from the literature examining the overall efficiency of cap-and-trade schemes versus tax regimes under uncertainty, parameterised for climate change and apply them to a focused analysis on the investment-incentives offered to a firm.

3. Model

We construct a three-period model to examine the effects of a taxation regime and a cap-and-trade scheme on the incentives to invest in a new carbon-abating technology in the presence of uncertainties. We construct a theoretical framework and parameterise the model to two example technologies, biomass for electricity and CCS, running the model under Monte-Carlo simulations. Our model generates returns to an investment in the technology over a three period time-frame (we use t to represent time period, $t \in \{1,2,3\}$) in comparison to a reference investment. We compare the distributions of these returns under the different instruments.

Our focus is on how the policy environment affects the incentives for any individual firm to invest in a risky low carbon technology. We allow for the possibility that the firm and the technology may be non-marginal to the system, i.e. that the firms choice may have non-negligible implications for the overall system's emissions and thus implications for carbon prices.

Specifically we analyse the incentives on a specific energy supplying firm, *F*, who can undertake an investment in a new technology, NT. The firm operates under a climate policy, either a tax or a cap and trade scheme. The remainder of firms operating under the climate policy are represented as a single system, *S,* and are assumed to not invest in the new technology.

We make a number of assumptions regarding the technology, the market characteristics and the abatement options open to the firm.

Technologies involved in abating emissions have very different properties. These properties affect how the introduction of such technologies amends the marginal abatement curve available to firms. We assume that the specific technology that we model has high initial costs prior to investment in comparison to the price of carbon produced by the carbon policy. Thus in order for such technologies to be deployed initially, at the time of the initial investment there must be some expectations of future profitability (infra-marginal rents) for the firm to make the initial investment. After the initial investment, the sunk cost no longer affects operational or pricing choices. Our aim is to generate the amount of returns a firm can earn over and above this sunk cost for the different instruments for given assumptions over technology and emission uncertainty.

In the interest of simplicity we assume that the firm faces the choice between two investments both yielding the same output which can be sold in the same market[3], one of which is the new technology and one of which is termed a reference option, *R*[4]. Essentially we assume the firm has a choice of investing in

[3] We assume that the firm is unable to pass on the carbon costs to the consumers of its product.
[4] This can be thought of as a standard high-carbon technology.

two plants which produce the same amount of product. This allows us to disregard the effect of the technology on other costs and the wider product market and focus solely on abatement and the impact of the carbon policy. The two investments are assumed to have different emissions levels and capital and operating costs. The new technology is assumed to have reduced emission levels and higher capital and operating costs in comparison to the reference option, and thus has a positive cost of abatement.

Our model utilises a defined marginal abatement curve for both the firm, A_t^F, and the system, A_t^S. This allows us to determine the price of carbon that is necessary to produce a level of abatement as defined by an assumed cap. We assume the firm has a wide range of abatement opportunities open to it which may result from a diversified plant portfolio and allows us to assume a continuous abatement curve for the firm, rather than a discrete series of options. Further we assume that there is a defined, monotonic (by definition) and therefore invertible[5] abatement function for both the firm and the system that determines the amount of abatement undertaken as a function of the price of carbon faced, whether through a carbon tax, T, or from purchasing allowances in a market, with price P. Furthermore we assume that these functions are stable over all periods in our model.[6] We assume this stability in order to simplify our analysis and define a single abatement curve for our model that remains for all periods. The assumption of stability effectively removes one element of uncertainty from our model, allowing us to focus on uncertainty regarding emission forecasts and the individual technology.

The new technology requires an additional level of investment I_t over the reference option, with an investment in period t resulting in a level of expected abatement, Q_{t+1}^{NT}, in the subsequent period $t+1$, implying a function $I_t = I(Q_{t+1}^{NT})$. This initial investment in the technology effectively creates additional abatement opportunities which are depicted by a new linear section in the abatement curve at an abatement cost of NT, k, up to a volume of Q^{NT} and shifts the abatement curve past this point (see Figure 3). The abatement cost includes both the operating cost of the technology and additional inputs that may be required in order to produce the same output of the good defined in terms of cost per ton of CO_2 abated.

[5] This is assumed in order for prices of permits and amounts of abatement to be determined in the model.

[6] This is a strong assumption. Work by Morris, Paltsey and Reilly (2008) and Klepper and Peterson (2006) have discussed the stability of the abatement curve with shifting global energy prices and policies in other regions. We assume stability as it allows us to have one abatement curve throughout the model and we can ignore any endogenity between factors in our model and the abatement curve.

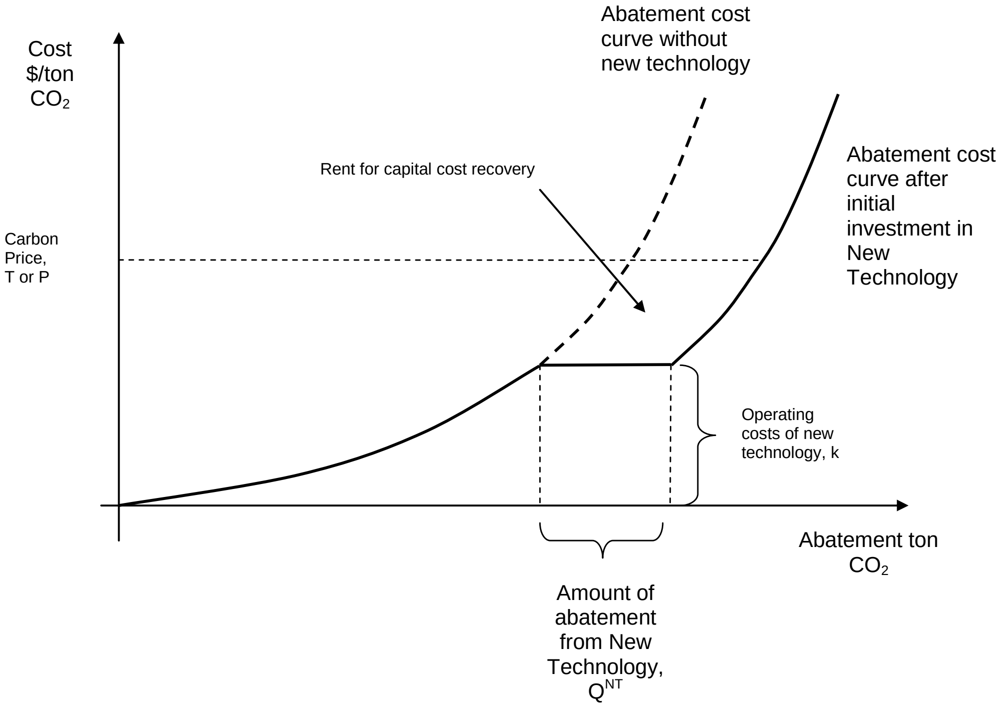

Figure 3: Effect of investment in new technology on the abatement cost curve

The government sets either the carbon tax T_t or the level of allowances that it auctions[7], E_t^{Cap}. There is a single market price that arises from these auctions, P_t, at which firms can purchase all the allowances it requires. Firms are required to purchase allowances for all of their emissions in any single period and there is no banking or borrowing of allowances and no external purchases of credits from other mechanisms. We define the variable Cap_t as the actual level of abatement required in the system as a whole. Cap_t is thus the difference between the level of emissions firms would produce without any climate policy, ($E_t^j \; j \in \{F,S\}$), and the volume of allowances offered for auction:

$$Cap_t = E_t^F + E_t^S - E_t^{Cap}$$

We determine prices in the carbon market using the intersection of the level of overall abatement required, Cap_t, and the overall abatement function of both the firm and the rest of the system, A_t^W.

$$A_t^W = A_t^S(P_t) + A_t^F(P_t)$$

We use the following function to determine the price emanating from the market:

$$P_t = \begin{cases} A_t^{W^{-1}}(Cap_t) & \text{for } A_t^{W^{-1}}(Cap_t) < k \\ P_t = k & \text{for } A_t^{W^{-1}}(Cap_t - Q_t^{NT}) \le k \le A_t^{W^{-1}}(Cap_t) \\ P_t = A_t^{W^{-1}}(Cap_t - Q_t^{NT}) & \text{for } k < A_t^{W^{-1}}(Cap_t - Q_t^{NT}) \end{cases}$$

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[7] We assume there is no initial free allocation of permits to firms.

where $A_t^{W^{-1}}(Cap_t)$ is the inverse of A_t^W defined at the level of abatement Cap_t. This allows the price to be determined for all cases, including when the technology is the price setter.

We model three periods in order to model a programme of investment, where firms commit to undertaking an initial investment followed by a second larger investment in the subsequent period.

In the reference option the firm undertakes investment in the reference plant in Period 1, and then is able to utilise the plant in Periods 2 and 3.

In the scenario where the firm undertakes investment in the new technology the following occurs:

- In Period 1, the firm undertakes investment in the new technology. This investment could be in a number of different forms. For example, it could be that the firm undertakes construction of a new coal plant fitted with CCS. The plant does not become operational until Period 2 and thus does not affect emissions or output revenues in Period 1.

- In Period 2, the firm can operate the new technology that they have invested in with a corresponding impact on both the firm and overall abatement function. As per the programme of investment there is a further investment in Period 2 which results in further deployment of the technology in Period 3. This allows us to model a situation where a firm builds one pilot plant initially, and then undertake a larger deployment, to further their experience and knowledge of the technology. Although these investments could be thought of as one single investment through staged payments we choose to model it as two separate investments to more closely represent the real-world decision-making and also to leave scope for future extension to the model where the second investment is contingent on various results from the first. At this stage we assume that the second investment occurs unconditional on the outcome of the initial investment.

  We assume that the level of investment in this Period is twice the scale of that which occurred in Period 1 and the resulting level of abatement in Period 3 is double that achieved in Period 2. We further assume a learning curve in investment costs related to the actual level of abatement in Period 2:

  $$I(Q_3^F) = \alpha I(Q_2^F)\text{, where } 0<\alpha<1$$

- In Period 3 the firm is able to operate both the technology from the realisation from investment in Period 1 and also the realisation of the technology from the subsequent investment in Period 2. The third period can be conceptually thought of as an extension of the second.

Our current model does not count benefits beyond Period 3 in order to simplify the analysis. There are, however, a number of possible reasons as to why the firm may not value benefits beyond this horizon in making their original commitment: firms may be expecting a mandate to implement the technology; they may discount heavily due to scepticism about sustained political commitment to the climate policy beyond this point; or they may be unable to harness their comparative advantage over the technology due to, for example, all firms having free access to the technology at this point. This does mean, however, that our model tends to underestimate the potential strategic returns to the investment that may result from being an early developer and investor in the technology.

As discussed above we examine costs solely in terms of abatement costs and compliance with the carbon policy as in our model the firms' choice of investment does not change their overall output or the market that they can sell it in.

In Period 1, costs to the firm under both scenarios are a function of the level of abatement undertaken, the level of emissions from the firm before abatement and the investment costs in the new technology.[8] In the reference scenario the last term of this equation is zero as there is no additional investment.

$$C_1^F = (E_1^F.P_1) - \int_0^{P_1} A_1^F(P)dP + I(Q_2^{NT})$$

In Period 2 in the new technology scenario, costs are a function of level of abatement, the level of emissions from the firm before abatement, the realised abatement from the new technology and the operating costs of the technology. Costs in period 3 are similar but without the additional investment.

$$C_2^F = E_2^F.P_2 - \int_0^{P_2} A_2^F(P)dP - (P_2 - k).Q_2^{NT} + I(Q_3^{NT})$$

$$C_3^F = E_3^F.P_3 - \int_0^{P_3} A_3^F(P)dP - (P_3 - k).Q_3^{NT}$$

We define the returns from investment as the present value of reduced costs for the firm in comparison to the reference scenario. In order to calculate this we compare the costs that the firm would face, with and without the investment in the new technology.

The total return under a cap-and-trade scheme in one time period is:

$$Return_t = (P_t - k).Q_t^{NT} + (P_t^R - P_t).E_t^F - \int_{P_t}^{P_t^R} A_t^F(P)dP - I(Q_t^{NT})$$

[8] We use the case of the cap-and-trade scheme as we set out our model. Unless otherwise stated the formulas are the same for the tax scheme, with P replaced by T.

where $t \in \{2,3\}$ and P_t^R is the level of the carbon price in the reference option with no investment in the technology.

Overall returns are the discounted sums of these Returns over all time periods.[9]

We build three main sources of uncertainty into our model: uncertainty over the emissions levels without abatement for both the firm and the rest of the system; uncertainty over the operating cost of the new technology; and uncertainty over the level of abatement from the initial investment.

In order to model the uncertainty over emissions levels, we assume that there is an emission 'shock' which affects both the firm and the system in Periods 2 and 3. This shock can be thought of as a change in general economic conditions which affects the output of firms, and therefore emissions. One complexity facing both firm and regulators is that such emission 'shocks' could occur at any time, and may or may not persist. To capture this we assume that there can be persistence in the shock across periods. In order to model this we use two correlated normal distributions.

$X_2 \sim N(0,\sigma_2^2)$ This is the shock that occurs in Period 2
$X_3 \sim N(0,\sigma_3^2)$ This is the shock that occurs in Period 3
$Cov(X_2, X_3) = \delta$ The covariance of the shocks that occur in Periods 2 and 3

Emissions of the firm in Period 2 are equal to the expected level plus a random draw from X_2 while emissions in Period 3 are equal to the expected level plus a random draw from X_3. The same draws, scaled up, are used to calculate emissions for the system.[10] The uncertainty in emissions levels before abatement implies that, although the government can define the level of emissions allowed with certainty, the level of abatement that this implies is uncertain.

We model technology uncertainty by making a random draw from a normal distribution $k \sim N(E(k), \sigma_k{}^2)$ where $E(k)$ is the expected operating cost of the new technology.

In order to model uncertainty over the outcome from the initial level of investment, we assume that the amount of abatement that the firm can utilise in Period 2 resulting from the firm's initial investment in Period 1 is uncertain. The actual level of abatement available is drawn from a uniform distribution $Q_2^{NT} \sim U(\alpha, \beta)$, where α is the lower bound and β the upper bound of abatement realised.

[9] These formulae work in the simple restricted case. In order to calculate returns for all cases we extend these formulae to examine cases where the new technology is marginal, or where all emissions are abated. See Annex 2 for full equations that operate in all cases.

[10] This implies perfect correlation between the shocks faced by the firm and the system. This may implicitly downplay the scale of uncertainty in the system as firms may face heterogeneous shocks to emission levels from those faced by the system.

Figure 4 gives a timeline of the model we construct, illustrating the three periods and the actions of the firm in each period.

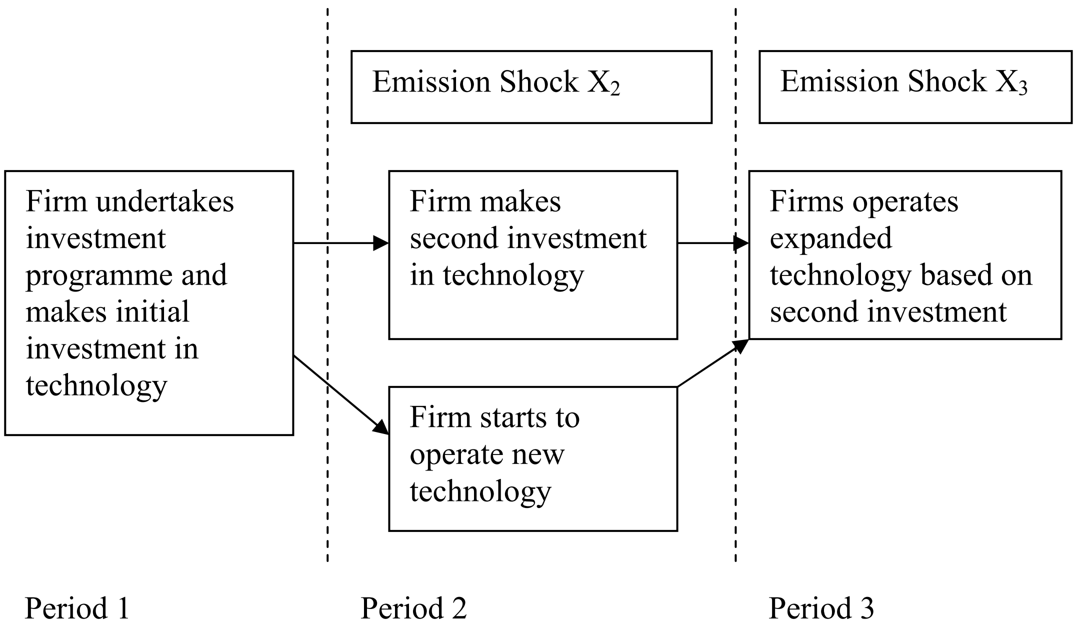

Figure 4: Timeline of the model

One of the key questions in comparing instruments is the basis for comparison: what is the suitable tax level for evaluation with cap-and-trade schemes. The choice of the tax level, like the decision on where to set the cap, is essentially a political decision and subject to a wider range of factors.

In our model we assume that the government has determined the desired level of emissions and sets E_t^{Cap} (the level of the cap under certainty) accordingly. When setting a tax it aims to set it at the level which, to the best of its knowledge, will meet this target.

We explore three different cases over how the government defines the tax given this objective:

- Case 1: The tax is set at the level necessary to meet the certain level of abatement in the reference scenario, with no new technology, and remains unchanged whether the firm invests or not. This implies larger returns to the cap-and-trade scheme under certainty as the firm benefits both from the drop in permit prices due to the introduction of the new technology and from the need to purchase fewer allowances.
- Case 2: The tax is set at the level necessary to meet the desired level of abatement assuming the maximum abatement from the new technology, if investment is undertaken. This essentially assumes that the government is optimistic with regard to the implementation of the new technology and only observes the best-case scenario.
- Case 3: The tax is set at the mean level of the carbon price upon implementation of the new technology, and takes into account the uncertainties over the final level of emissions. Due to the convexity of the

abatement function this is higher than the level of tax that is required given a certain level of abatement.

The choice of tax between the three cases is, in essence, determined by the speed of adjustment of the government to new technologies and the level of information available. The first case represents where there is no, or extremely delayed adjustment once new technologies appear; the second when there is no uncertainty taken into account; and the third, where the government observes the technology and the uncertainty but can only set the level of tax once every period.

One instrument that has been proposed to improve the performance of cap-and-trade schemes is the use of price floors and ceilings. Floors may be operationalised by setting a reserve price on auctions (Hepburn et al 2006, Grubb and Neuhoff 2006). Option contracts are an alternative mechanism through which floors could be introduced. Ceilings can be introduced by a commitment to release extra allowances into the system when the ceiling is reached. We introduce price floors and ceilings to the cap-and-trade scheme in order to examine the impact of these instruments.

4. Data Description

We parameterise the model with two example technologies, Biomass for electricity and CCS, the specific details of which are discussed below.

We choose the firm size to approximately mimic the size of a large diversified energy supplier, namely EON, and we set the system to approximately match the remainder of the operators under the EUETS.

We define the input data annually and assume that each period, *t*, is of five years duration, with both cost data and returns delineated in 2005 US$. We aggregate and discount annual surpluses into total surpluses for each period and use the weighted-average capital cost to EON before taxes as the discount rate (9.1%).

We draw abatement functions for both the firm and the system from the IIASA GGI scenario database (IIASA 2007). The scenario provides discrete points for shadow prices of GHG and emissions for Europe as a whole, from which we draw a continuous function. We scale this down to fit the size of the EUETS relative to European emissions in total.[11] We assume that the firm represents approximately 5% of the total trading scheme (approximately the size of EON)

[11] By doing so, we are implicitly assuming that the EUETS has the same mitigation options available to it as Europe as a whole, and that the firm has the same options as the system. This is an abstraction given that it is likely there are a number of lower-cost mitigation options available to Europe (energy efficiency being perhaps the clearest example).We use data for both WEU and EEU which also include non-member states, Albania, Bosnia and Herzegovina, Croatia, FYR Macedonia, Serbia, Switzerland and Turkey. We scale the function by half to reflect the size for the ETS compared to the total area, and also the reflection that more of the abatement is likely to occur in the ETS compared to the area as a whole.

and we scale the abatement function accordingly. We set a declining cap over the three periods for emissions similar to that conceived for the EUETS phase III.

In defining the scale of uncertainty in both emissions and technology, we draw upon previous literature. We use work from previous estimations of future ETS emissions to determine the approximate scale of uncertainty over emissions (CamEcon 2009). We choose an approximate range of $\pm$110 Mt CO_2[12] a year for the system as a whole with firm uncertainty scaled accordingly.

The specific shocks to the firm's emissions we assume are:

Shock in Period 2 $X_2 \sim N(0,31.25)$

Shock in Period 3 $X_3 \sim N(0,31.25)$

Covariance of shocks $\delta = 0.5$

We choose these distributions in order to give both the range of uncertainty that we discuss above and also identical variances in both periods.[13]

We summarise the data for all variables and the form of all functions in Annex 1. As discussed above, in comparing cap-and-trade with tax, there are various options for defining tax levels. In table 1 we show the levels of carbon tax we derive for all three cases of tax formation and for the two different technologies.

	Tax Case 1	Tax Case 2 Without Investment	Tax Case 2 With Investment Biomass	Tax Case 2 With Investment CCS	Tax Case 3 Without Investment	Tax Case 3 With Investment Biomass	Tax Case 3 With Investment CCS
Period 1	19.01	19.01	19.01	19.01	19.01	19.01	19.01
Period 2	41.81	41.81	40.94	41.27	47.88	47.29	47.58
Period 3	73.48	73.48	70.06	71.33	79.43	76.6	77.95

Table 1: Levels of Carbon Tax ($/t$CO_2$)

There has been relatively little work conducted on at what levels instruments such as price floors and ceilings should be set, thus we chose to set a floor and a ceiling to cut off a certain percentage of the distribution of carbon prices. We set a floor price to cut off the bottom 20% of the frequency distribution of carbon prices, given the uncertainties discussed above, and a price ceiling that cuts off the top 20% of the frequency distribution of prices. The subsequent results should thus be seen only as an indication of the potential impact of introducing a floor or ceiling and not as representing any particular optionality or expectation.

	Price Floor	Price Ceiling
Period 2	19.48	72.82
Period 3	41.11	111.44

Table 2: Levels of Price Floor and Ceiling ($/t$CO_2$)

[12] Thus we set the standard deviation to approximately 110 Mt CO_2 so that 95% of observations fall within this range

[13] These variances imply a standard deviation of 111.80 for the system as a whole, reflecting the range of estimates of emissions projections.

▪ 4.1 Biomass

We first run our model for electricity-generating biomass plants. These have a similar cost structure as assumed in our model in terms of significant capital and subsequent operating costs. Biomass for power is a relatively mature technology with relatively low uncertainty over the technology involved. There are still large questions, however, over the supply chain for the fuel inputs and the load factor at which such plants could operate.[14]

We assume that the firm operates the technology as baseload, operating it without reference to the carbon price. If the price of carbon, P, falls below the operating costs of the technology, k, the firm operates biomass over the most expensive abatement options it would have undertaken without the technology.

We use a reference scenario investment of a 500MW supercritical coal-plant drawing on data on capital costs, operating costs and emissions from the Integrated Environmental Control Model (IECM 2006).[15]

We draw data for biomass for capital and operating cost from a study by Caputo et al (2005), and a study by the European Commission (2008). We estimate additional capital investment at $190 million for construction of 10 50MW biomass fired power plants[16] in comparison to the reference scenario.

Estimates for the range of operating costs are drawn from both studies and the range observed there have led to us choosing a distribution for the abatement cost as:

Abatement cost of Biomass for power $ per ton carbon

$$k \sim N(34,9)$$

As emissions from biomass do not have to be accounted for under the EU ETS, abatement is equal to the emissions produced by the alternative investment, the supercritical coal plant. We assume that there is uncertainty over the load factor for the biomass plant, which realises itself as uncertainty over the level of abatement vis-à-vis the alternative investment[17]. We model this uncertainty with a uniform distribution:

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[14] We make the assumption that the firm does not face constraints over the supply chain for the biomass power plant and thus can operate the plant as baseload generation.

[15] Due to the estimate base load for the biomass plants the actual size of the plant is 596.5MW. We use the standard assumptions in the IECM model for a SCR+ESP+FGD plant, with the exception of the coal price which we amend to $70/t in order to reflect the higher prices in the EU.

[16] This is based upon data from Caputo et al (2005) for capital investment in 10 50MW plants utilising fluid bed composition followed by steam turbine cycle generation, using a biomass composed of agricultural crops by-products, agro-industrial and wood wastes.

[17] We implicitly imply here that the firm can produce the same amount of product despite varying load factor, this may imply the use of small amounts of fossil fuel input and thus reduce the abatement that is possible vis-à-vis the reference plant.

$$Q_2^{NT} \sim U(2.2, 3.2)$$
$$Q_3^{NT} \sim U(6.6, 9.6)$$

where the upper bound of abatement is based upon emissions from the reference plant drawn from IECM (2006).

The investment function, $I(Q_t^{NT})$, is parameterised as a linear function using the upper bound level of abatement with the figure for additional capital investment.

We assume a learning curve that affects this investment function that depends on the actual realisation from the initial investment. Capital costs fall by approximately 5% from a full realisation of abatement, declining as the realisation falls (for full parameterisation see Annex 1).

4.2 CCS

CCS is an additional technology, whose cost and risk structure is broadly appropriate to our model structure. It is a technology that is likely to require large initial investments in terms of capital/learning costs, but will also require significant operating costs beyond this investment. The initial investment may open opportunities for wider deployment of the technology, and may be externally funded, at least partially, through government support. CCS is an immature technology, in comparison with biomass for power, with greater uncertainty over costs and performance.

Along with this greater scale of uncertainty CCS has further differences from biomass. In that it is not central to generation of the product it is possible for the abatement technology to be switched off whilst the product can still be produced. This may be the case if the carbon price falls below the level of operating cost of the technology. With this in mind we make an amendment to the model used for biomass to allow the firm to choose to abate or not depending on the carbon price and the operating cost of the technology.[18]

In its operation CCS consumes a percentage of a plant's output, implying that factors such as the electricity-carbon price spread will play a role in its investment incentives and decision to operate.[19] By allowing a bound of uncertainty over the operating cost of the technology, which includes costs of forgoing electricity we implicitly include this factor, but do not model electricity prices explicitly.

[18] The amendment to the equations are outlined in Annex 2.

[19] CCS is a relatively unique technology in that it is consumes some of the output of the plant when it is in operation, consuming roughly a third of the plant's supply. This can be recovered, however, by switching off the technology. Thus, the choice between operating the plant with and without CCS depends on what the firm can gain from selling the extra output, versus the extra cost it incurs from the carbon price. For instance, when carbon prices are low and it is uneconomic to run the technology, the firm can gain from producing and selling the extra electricity.

We draw data, for capital investment, operating costs and abatement from IECM (2006) and maintain the reference scenario as an investment in a 500MW supercritical coal plant[20]. Additional capital investment for construction of a plant with CCS is $450 million, which covers both the cost of the CCS and the cost of constructing a larger plant which is required to match the output of the reference plant due to CCS consuming a percentage of the plant's output.

For the range of uncertainty regarding the technology, we surveyed a range of literature (IECM 2006, IEA 2008, IPCC 2005, Rubin et al 2007, McKinsey 2009) and chose an approximate scale of uncertainty based upon the range of estimates given.

Operating cost of CCS, in $ per ton carbon abatement

$$k \sim N(35,25)$$

Abatement for CCS, $MtCO_2$ is also drawn from these studies and determined in comparison to the plant without CCS. The distribution chosen is:

$$Q_2^{NT} \sim U(1,2)$$

with the upper bound drawn from abatement level from IECM (2006).

We parameterise the investment equation in the same manner as for biomass and assume the same learning curve over capital investment.

5. Results

We run Monte-Carlo simulations of 50,000 observations each, for both technologies, for the three cases of tax formation and for cap and trade schemes with and without the use of price floors and ceilings. We obtain net present value surpluses under the various instruments, which we aggregate into histograms to obtain a distribution of net present value surplus returns. Full results can be found in Annex 3[21].

We find that in two out of three cases, cap-and-trade schemes generate a higher mean, but also a greater distribution in, returns over investment than under tax regimes. This higher mean is evident when the tax is set as per Case 1 and 3, with the tax showing a slightly higher mean when the tax is set as per Case 2.

In a cap-and-trade scheme the price adapts to states of the world where emissions are higher or lower than expected. The convexity of the marginal

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[20] We compare between a super-critical coal plant of 500MW without CCS and a 661.4MW plant with CCS to ensure that the annual power generation is equivalent, following the same assumptions as the reference plant in the biomass case.

[21] Note that the results for each technology are drawn from six separate simulations. The reported results for the cap and trade scheme and cap with floor are drawn from the same simulation as for Tax Case 1. The comparison of returns over investment between instruments utilise the results for the cap and trade scheme in the different simulations. There are small differences between these simulations, thus the results for the comparison between instruments may not tally with the returns over investment.

abatement curve implies that in our model higher than expected emissions drive carbon prices higher than they would fall due to lower than expected emissions. As these carbon prices are a key determinant of the returns to the technology the higher returns under higher than expected emissions outweigh the lower returns when there are lower than expected emissions. The tax is unable to adjust to these changes in expected emissions.

5.1 Results for Biomass

When we apply the model to biomass for power we observe positive mean returns under all instruments.

Under a tax, set as per case 1, mean returns over investment are $191 million with a standard deviation (σ) of 88 million with zero or greater returns observed in 99% of cases. Under a cap and trade scheme mean returns over investment are $657 million (σ=873 million) with zero or greater returns observed in 78% of cases. The cap in comparison to the tax generates a greater average return of $467 million, with the cap generating greater or equal returns in 71% of cases.

When we amend the tax to case 2, we assume the government has knowledge regarding the technology and sets taxes based upon the upper bound of abatement arising from it. In this case the average mean return over investment under the tax increases to $669 million (σ=92 million). The advantage of cap-and-trade schemes over taxes decreases in this case as both the tax level and the price of carbon adjust to the introduction of the technology. We observe that the tax provides an average surplus of $10 million over cap-and-trade (σ=853 million), with the cap generating greater or equal surpluses 47% of the time.

With our final amendment to the process of tax formation, where the government has knowledge of the technology and also the scope of the uncertainty, we observe that the returns under the tax over investment reduce to an average of $652 million (σ=99 million). The advantage of cap-and-trade schemes over tax returns with a mean return over the tax of $3 million (σ=830 million), with the cap generating greater or equal surpluses 48% of the time. Figure 5 shows the distribution of the returns we obtained over investment for the tax under case 3 and a cap-and-trade scheme.

We examine the use of price floors and ceilings as amendments to standard cap-and-trade schemes. When we compare the instruments, we find that the scheme with the floor generates a greater return vis-à-vis the tax compared with the standard scheme.

The introduction of price floors raises the mean return of investment by $52 million (σ=148 million) with respect to the standard cap-and-trade scheme, with returns greater or equal in 93% of cases. The floor causes these effects by reducing the lower end of returns when emission shocks are negative and carbon prices collapse, as prices only fall to the level of the floor.

Price ceilings reduce the advantage of cap-and-trade schemes over taxes with returns lower than taxation in two cases. With price ceilings and floors we observe that the mean return to investment falls, with the instrument with floors and ceilings producing mean returns that are-$187 million (σ 515 million) lower than a standard scheme. This is due to the fact that the ceiling reduces the number of cases when high surpluses are obtained, as high carbon price scenarios are removed. Despite these effects the instrument with ceilings and floors generates a greater return than taxes in the majority of cases where, due to the floor reducing low returns from low carbon price scenarios. Figure 6 illustrates the returns over investment under the tax in case 3, in comparison with the standard cap-and-trade scheme and a scheme with a floor and ceiling. There are two clear spikes in the distribution around the level of returns associated with cases of the world where either the floor or ceiling is enacted in both periods, i.e. the spike at the left hand side of the distribution is associated with floors being active in both periods, and the spike on the right hand side is related to ceilings being enacted in both periods.

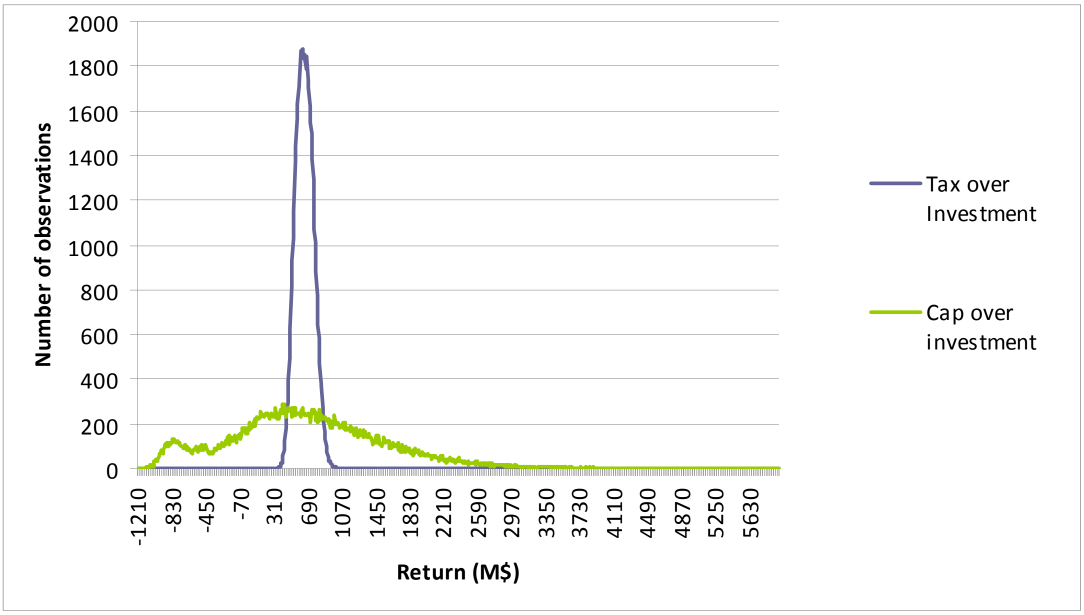

Figure 5: Distribution of returns over investment under tax case 3 and a cap and trade scheme

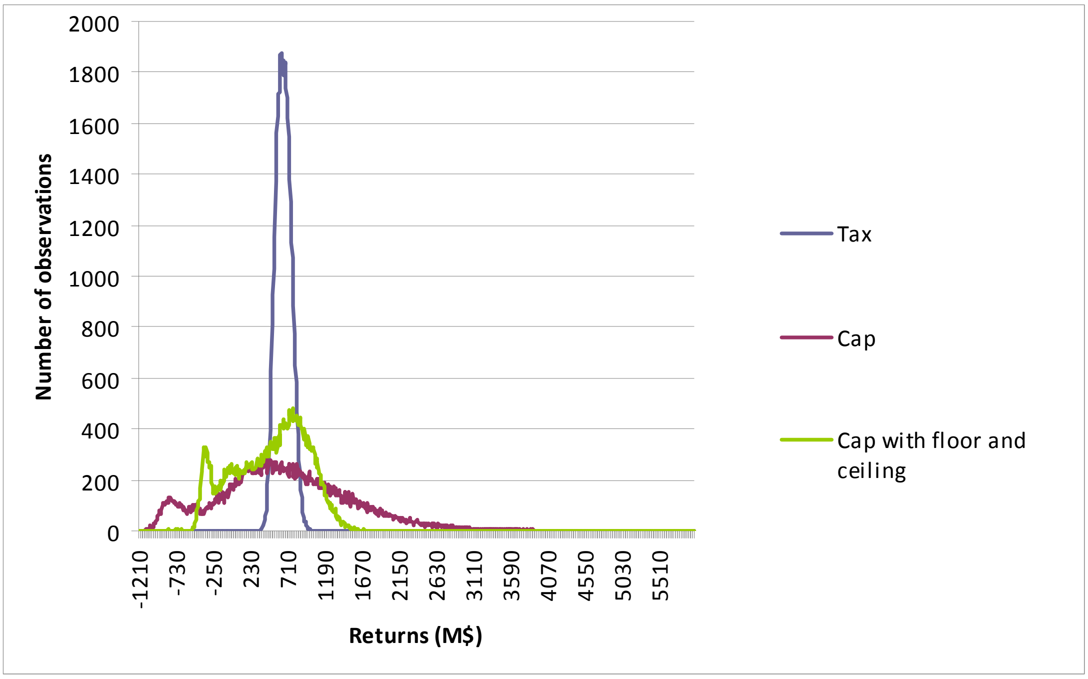

Figure 6: Distribution of returns over investment for a tax, cap-and-trade and cap and trade with floor

5.2 Results for CCS

When we apply our model to CCS we find that, under the assumptions we have made, mean returns from the technology are negative under all cases of tax formation. The mean returns vary between -$616 million (under case 1) to -$302 million (under case 2). In all cases we find less than 0.01% observations of zero or greater returns.

We find that a standard cap-and-trade scheme generates a mean return of -$307 million over investment, with a standard deviation (σ) of $467 million. Positive observations are observed 22% of the time. When comparing the returns under a cap-and-trade scheme in comparison to tax under case 3 we find that the cap generates a greater or equal return in 48% of cases, with a greater mean surplus of $40 million.

These results underline that the levels of cap and carbon tax levels potentially debated, are in general insufficient to make CCS investment economic over the next 15 years without government support. This is in stark contrast to the results for biomass where, for the assumptions we make, both caps and taxes generate positive mean returns in all cases. Despite the negative returns the choice of instrument does have a strong bearing on the size of deficit and hence the scale of additional support that may be required.

In Figure 7 we compare the distribution of returns under a cap-and-trade scheme and a tax determined as per case 3. We observe a spike in observations for the cap-and-trade scheme, caused by the large amount of cases where the carbon prices is not high enough, in either period, to operate the technology and thus the surplus is equal to the investments in the technology. In the tax case we do not observe this as the tax level is sufficiently high so that in at least one period it is higher than the operating cost and thus the technology is operated.

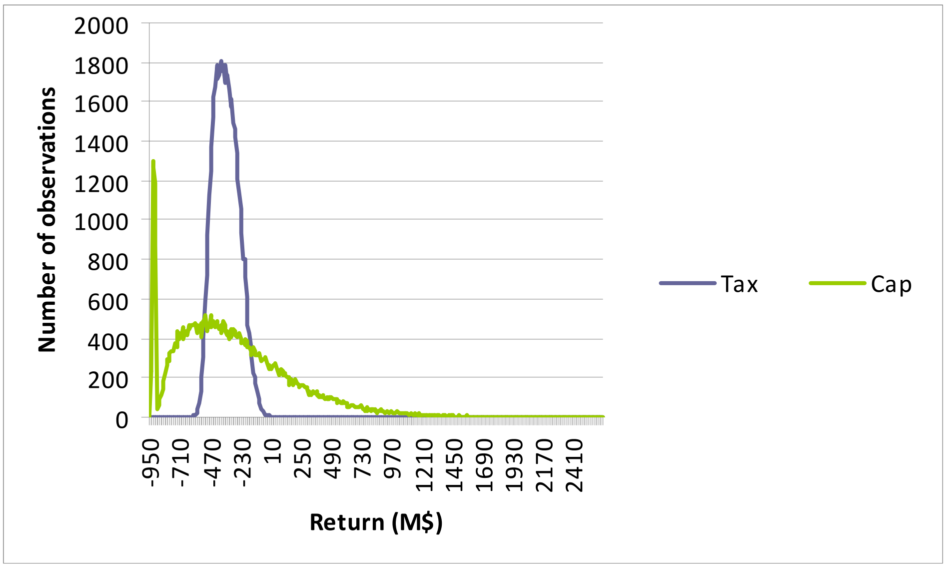

Figure 7: Distribution of returns under tax case 3 and a cap-and-trade scheme compared to investment

When we introduce price floors and ceilings to the cap-and-trade scheme, we observe similar results to those found under biomass.

We find that the scheme with the floor generates a greater return compared with the standard scheme (returns are on average $1 million higher (σ =28 million)) and generates a greater or equal return in 94% of cases.

When we introduce the ceiling along with the floor, the average return from the instrument over a standard cap-and-trade scheme falls to -$137 million (σ 269 million) although 62% of the time the instrument still generates greater or equal returns than a standard cap. Figure 8 compares the distribution of returns under a tax, cap-and-trade and cap-and-trade with price floors and ceilings.

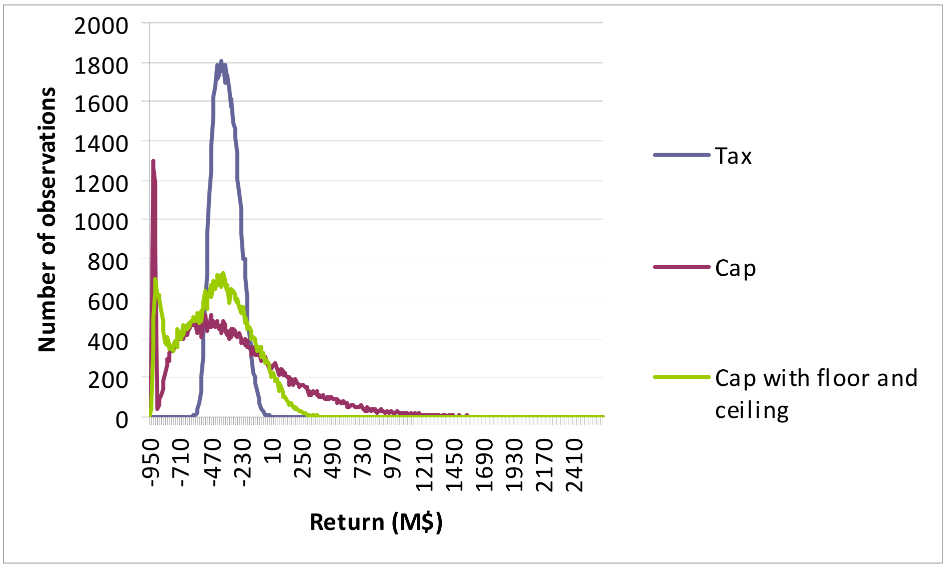

Figure 8: Distribution of returns over investment for a tax, cap-and-trade and cap and trade with floor and ceiling

▪ 6. Policy Implications

Our comparison of the differing firm-level incentives to investment in new technologies produced by different instruments offers a range of insights for policy.

The ability of carbon prices to react to uncertain states of the world produces, in two cases of tax formation, higher average returns for cap-and-trade schemes than for tax regimes, These returns are driven by states of the world with high carbon prices, driven by higher than expected emissions. The average returns from the cap-and-trade scheme are associated with a higher distribution of returns than under taxes, thus the risk-preference of the firm must be taken into account when deducing which instrument creates the greater overall incentive for investment.

In standard economic theory, firms require higher returns when there is higher risk. Whether the higher returns on average under a cap-and-trade are enough to counter-balance the higher risk is uncertain and therefore, so is whether cap-and-trade schemes truly give greater incentives. Given that floors both increase the average and reduce the distribution of returns, they are likely to improve the incentives for investment from cap-and-trade schemes whatever this risk preference, although they may increase the cost of compliance for the firm as a whole. The effect of ceilings is more ambiguous. Although they reduce the overall distribution of returns, they also reduce the average return, and it is not certain which of these effects dominates with regard to the overall incentive to investment.

It is important to stress that investment must also be placed in context of the wider risks facing the firm. We find that returns to low carbon investment are highest under a cap-and-trade scheme when emissions are at their greatest due to positive shocks. It is likely that this will occur when the economy is strong and demand for electricity is high. This implies that returns to such investment are highest when revenues for the firm are likely to be at their highest, thus amplifying the risk faced by the firm. In contrast it is in these times that the costs of compliance with the carbon policy are also likely to be highest, so investments in such technologies can help hedge some of the risk associated with such compliance.

There is a question as to how probable states of the world with higher than expected carbon prices are. In two cases so far (EU ETS phase I and phase II) there have been dramatic price falls caused, at least in part, by over-allocation of emission permits. There are certain mitigating circumstances for this. Phase I was essentially a trial and thus the over-allocation can be seen as part of the learning experience; while phase II has taken place within the backdrop of the largest economic recession in living memory. Despite this there are questions as to whether the distribution of emissions should be modelled as per a normal distribution or whether there are longer tails on the downside than the upside. This may be the case if there are systematic reasons why emissions or the projected costs of meeting caps are overestimated, causing caps to be set too high (for a discussion of such reasons see Grubb and Ferrario 2006).

The choice of the tax level, like the setting of the cap, is a political decision and thus subject to a wide variety of factors. We examine different methods for tax formation and find that the performance vis-à-vis the cap-and-trade varies accordingly. We vary the tax based upon three different cases, where governments have varying ability to predict future technologies and calculate uncertainty. We find that taxes perform best when governments make the most optimistic assumptions regarding the technology. Given the inertia often in place in government regulation and tax-setting, it is questionable how well governments can set taxes that take into account these factors, and thus how well the tax can perform in practice.

Cap-and-trade schemes are associated with a greater distribution of returns, and thus a greater degree of risk. Price floors and ceilings are two instruments that can be used to mitigate some of the risk associated with cap-and-trade schemes as they remove states of the world with very low or very high carbon prices. The use of floors in our model reduces the distribution of returns and increases the average return over a standard cap-and-trade scheme in the range of $1-59 million NPV for the levels chosen, thus improving incentives for investment no matter the risk preference of the firm. The use of ceilings reduces the distribution of returns and also decreases the average return by approximately $140-190 million NPV over cap-and-trade schemes for the levels chosen, thus its effect on investment incentives is ambiguous and depends on the firms' appetite for risk.

The introduction of price floors and ceilings to cap-and-trade schemes raises the prospect of competing incentives. Firms may prefer price ceilings as they can cap the cost of compliance with the carbon policy, yet they reduce returns to investment in new low-carbon technologies. The scale of these competing incentives will depend on the structure of the generation capacity of the firm, with firms who rely more heavily on high-carbon generation having greater incentives for price ceilings, in comparison to firms with a greater low-carbon generation base.

There are important questions to be answered over the level at which floors and ceilings should be set to maximise incentives to firms, but also to enable sufficient emission reductions and to minimise overall costs of compliance. Examining a curve of returns weighted by frequency allows some insights into the levels of floors and caps that might be effective. Figure 9 displays this curve for carbon prices averaged over Period 2 and Period 3 for both technologies. The curve highlights that for CCS average carbon prices over \$85/t average returns are positive[22], whilst for biomass this level is \$39/t. This highlights that a price floor placed at \$85/t would remove the vast majority (although not all) of negative returns for CCS, whilst for biomass one at \$39/t would be sufficient. A ceiling at \$150/t would still preserve the vast majority of returns (81% of the positive probability-weighted returns for CCS, and 95% for biomass).

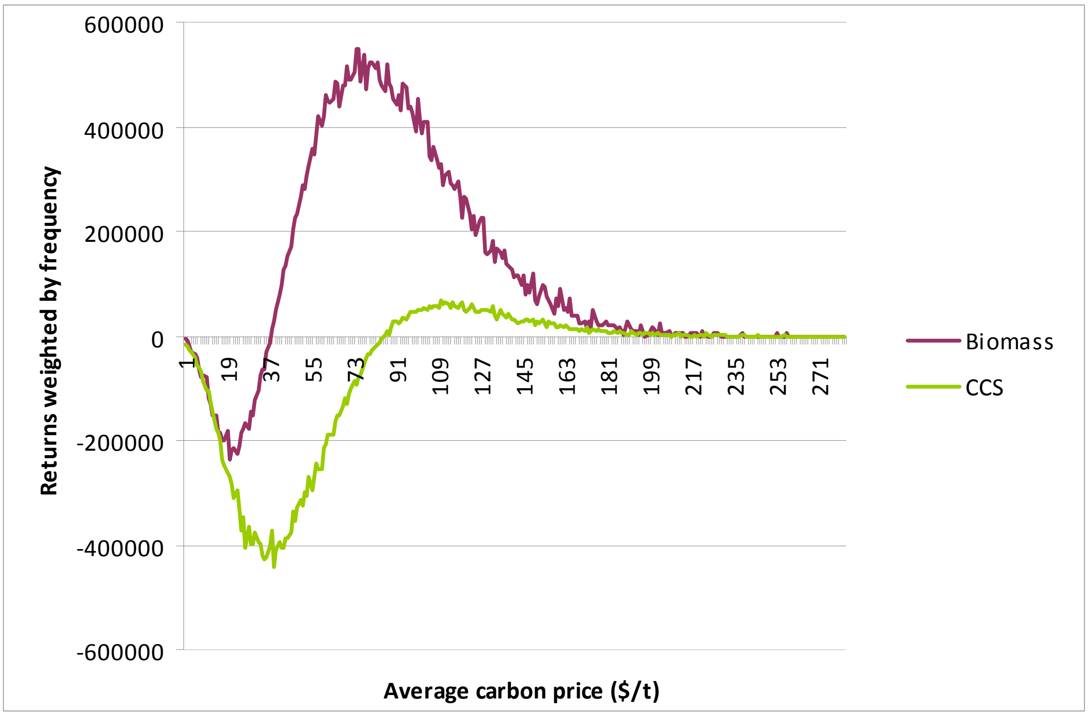

Figure 9: Returns weighted by frequency against average carbon prices in Period 2 and Period 3

Although the aim of our model is to examine the effect of instrument choice, rather than to fully model the investment decisions surrounding either technology there are some broad conclusions regarding the technologies that we can draw.

[22] Although individual returns for carbon prices can be negative. We found that for our assumptions the lowest average carbon price for which there are no negative returns observed was \$136/t

For one of the technologies we model, CCS, we find that given our assumptions over the technology and the evolution of the carbon policy, the programme of investment is uneconomic under both instruments over the 15-year period modelled. This may highlight why there is a relative lack of private investment in a technology that is anticipated to play a large role in energy generation in the coming decades. The negative returns could be thought of as the cost to the firm of 'building the option' of future deployment of the technology and whether such a cost should or could be borne by a firm or covered by external funding, such as government support, depends on the importance placed on the technology. If it is left to a firm, given the uncertainties over the returns and the scale of shortfall there are large risks that the risk-averse nature of firms may stymie investment, even with a carbon policy in place.

The negative returns highlight the scale of external support that may be required in addition to a carbon instrument. For CCS the EU will allocate a small number of EUAs to plants operating the technology in the next phase of the EUETS. This is unlikely to mitigate the risks to the company as it is in low price scenarios that firms receive the lowest returns to investment, and it is also in these scenarios when such a subsidy would be worth the least.

When we apply the model to biomass for power, for the assumptions we have made over scale, cost and abatement, all instruments produce positive returns. This highlights that for this technology there may be less justification for further external support on the scale of that that might be required for CCS.

7. Conclusions

Meeting the challenge of climate change is likely to require large investments in new technologies. Our model shows that different instruments for carbon policy create different incentives for firms to invest in new abatement technologies.

We build on existing work examining the choice of pollution abatement instrument on incentives to invest in new technology. By building in uncertainty and parameterising our model with assumptions relevant to the climate change problem and for suitable technologies, we also more closely model the incentives for investment in carbon-abating technologies. We build on literature such as Weitzman (1974), Pizer (2002) and Weber and Neuhoff (2009) that examines the choice of instrument between taxes and quantity constraints from an overall societal perspective for both pollution generally and climate change in particular, developing this work, focusing more specifically on the firm-level incentives that these instruments provide. By parameterising our model we move toward examining the firm-level preference for such instruments when investing in new, uncertain technologies.

Under our assumptions and for the time period modelled cap-and-trade schemes yield greater returns on average than taxation in two out of three cases, yet with a larger distribution of returns. This is driven by the convexity of the abatement function and states-of-the-world with high carbon prices. Whether the higher return is enough to compensate for the higher risk depends on the risk preference of the firm. The levels of both setting the cap and also the level of tax are political decisions. We investigate three different cases of tax formation, depending on the speed of adjustment of the government and the level of information taken into account. Taxes that are set with information regarding the investment and the technology perform best.

The introduction of price floors and ceilings amend the performance of cap-and-trade schemes with regard to both average returns and risk with respect to incentives to investment. In our model, for the assumptions we have made over technologies, floors improve both the mean and the distribution of returns, while ceiling reduce the distribution but also the mean. The overall incentives offered by the second depend on the risk-preference of the firm. There is a dichotomy here in that the introduction of floors can increase the overall cost of compliance for a firm as a whole but may increase the incentives for investment in any single low-carbon project.

Our work fills a gap in the current literature in modelling the firm-level incentives emanating from different instruments for a programme of investment in a low-carbon technology in an uncertain world. It highlights the differences between the instruments in both the mean, and the distribution, of the returns to such an investment. As both tax and cap-and-trade schemes differ in both of these facets, the risk-preference of the firm is important in determining the actual incentives offered. Future work investigating this area would be valuable in determining such incentives. The overall impact of instruments such as price floors and ceilings, amend the incentives for investment into a single technology to the firm. This needs to be placed in the wider context of the firm, however, as they will also amend the overall cost of compliance. The incentives offered by these instruments depend on the levels at which they are initiated. Future research would be valuable in answering the questions that arise in this area. Since political economy considerations may anyway create strong pressures for a price cap, there are many reasons to investigate the properties of hybrid instruments – cap-and-trade with price collars – and additional research in this area will be crucial.

▪ Acknowledgements

The authors acknowledge the financial support of the ESRC Electricity Policy Research Group. The authors would like to thank Adam Rysanek for his valuable assistance with this work and also the members of the Electricity Policy Research Group and an anonymous referee for their constructive comments.

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- **Annex 1: Data used in model**

Variable	Value	Unit	Source
Firm's emissions E^F	87	Mt CO2e	Representative of EONs ETS emissions
System Emissions E^S	1920	Mt CO2e	Representative of remainder of trading scheme
Cap Period 1, Cap_1	1800	Mt CO2e	
Cap Period 2, Cap_2	1700	Mt CO2e	
Cap Period 3, Cap_3	1600	Mt CO2e	
Discount Rate	9.1	%	EON's reported Cost of Capital 2008
Overall abatement function	$C = 0.000436.A^2$	C is in \$/ton A is in Mt	Function from GGI scenario database for WEU for 2020 from B1 scenario. Scaled to represent ETS
Firm 1 abatement function	$C = 0.17744.A^2$	C is in \$/ton A is in Mt	Scaled function of overall abatement
Amended abatement function	$C=0.0006132A^2$	C is in \$/ton A is in Mt	Scaled function of overall abatement
CCS Investment, I	450	M\$ US	Additional capital expenditure required to build Supercritical coal plant with CCS with same output as 500MW plant without (from IECM model)
Amount of CCS abatement, lower bound, α	1	Mt CO2e	
Amount of CCS abatement, upper bound, β	2	Mt CO2e	The amount of CO2 avoided with CCS plant (from IECM model).
Abatement cost of CCS, k	35	\$/t CO2e	From difference in O&M costs in plant with and without CCS
Learning curve	$I(Q_3^{NT}) = \phi^{(1-0.015Q_2^{NT})}.(E(Q_3^{NT}) - E(Q_2^{NT}))$		where ϕ is the amount of investment required for abatement of one $MtCO_2$ in a year.

Biomass Investment	190	M$ US	Additional capital expenditure required to build 10 50MW biomass plants with over supercritical coal plant with same output
Amount of Biomass abatement, lower bound, α	2.2	MtCO2e	
Amount of Biomass abatement, upper bound β	3.2	MtCO2e	
Abatement cost of biomass, k	34	$/t CO2e	

- **Annex 2: Full equations**

Tax Case

$$C_1^F = (E_1^F . T_1) - \int_0^{T_1} A_1^F(T)dT + I(Q_2^{NT})$$

$$C_2^F = E_2^F . T_2 - \int_0^{T_2} A_2^F(T)dT - (T_2 - k).Q_2^{NT} + I(Q_3^{NT})$$

$$C_3^F = E_3^F . T_3 - \int_0^{T_3} A_3^F(T)dT - (T_3 - k).Q_3^{NT}$$

The following equations hold for $t \in \{2,3\}$

T_t^a defined as the value where $E^F = A(T_2^a) + Q_2^{NT}$

T_t^b defined as the value where $E_t^F = A(T_t^b)$

$$\Delta T_t^a = \frac{((T_t - k) + (T_t - T_t^a)) - \left|(T_t - k) - (T_t - T_t^a)\right|}{2}$$

$$\Delta T'^a_t = \frac{(\Delta T_t^a + 0) + \left|(\Delta T_t^a - 0)\right|}{2}$$

$$\Delta T_t^b = \frac{((T_t - k) + (T_t^b - k)) - \left|(T_t - k) - (T_t^b - k)\right|}{2}$$

$$\Delta T'^b_t = \frac{(\Delta T_t^b + 0) + \left|(\Delta T_t^b - 0)\right|}{2}$$

$$Return_t = C^F_{t\ NT} - C^F_{t\ R}$$

$$\chi_t = E_t^F . \Delta T'^b_t$$

$$\varepsilon_t = \int_k^{T_t - \Delta T'^a_t} A^F_t(T) + Q^{NT}_t \, dT + E^F_t . \Delta T'^a_t$$

$$\theta_t = (k - T_t).Q^{NT}_t + \int_{T'}^{T_t} A_t(T)dT - (A^F_t - Q^{NT}_t).(T_t - T')$$

where $T' = A^{F^{-1}}_t (A^F_t - Q^{NT}_t)$

$$\varphi_t = \frac{(\theta_t + 0) + |\theta_t - 0|}{2}$$

$$Return_t = \frac{(\chi_t + \varepsilon_t) - |(\chi_t - \varepsilon_t)|}{2} - \int_k^{k+\Delta T'^b_t} A^F_t(T)dT + (E^F_t(T^R_t - T_t) - \int_{T_t}^{T^R_t} A^F_t(T)dT - I(Q^{NT}_{t+1}) - \varphi_t$$

$$OverallReturn = \sum_{t=1}^{t=3} \mathrm{Re}\,turn_t$$

<u>Cap and Trade Case</u>

$$P_1 = A_1^{S+F^{-1}}(Cap_1)$$

$$C^F_1 = (E^F_1 . P_1) - \int_0^{P_1} A^F_1(P)dP + I(Q^{NT}_2)$$

$$C^F_2 = E^F_2 . P_2 - \int_0^{P_2} A^F_2(P)dP - (P_2 - k).Q^{NT}_2 + I(Q^{NT}_3)$$

$$C^F_3 = E^F_3 . P_3 - \int_0^{P_3} A^F_3(P)dP - (P_3 - k).Q^{NT}_3$$

The following equations hold for $t \in \{2,3\}$

$$P_t = \begin{cases} A^{W^{-1}}_t(Cap_t) & \text{for } A^{W^{-1}}_t(Cap_t) < k \\ P_t = k & \text{for } A^{W^{-1}}_t(Cap_t - Q^{NT}_t) \le k \le A^{W^{-1}}_t(Cap_t) \\ P_t = A^{W^{-1}}_t(Cap_t - Q^{NT}_t) & \text{for } k < A^{W^{-1}}_t(Cap_t - Q^{NT}_t) \end{cases}$$

$$A^F_t = A^F_t(P_t) \, for P_t < k$$

$$A^F_t = Cap_t - A^S_t(k) \, for P_t = k$$

$$A^F_t = A^F_t(P_t) + Q^{NT}_t \, for P_t > k$$

P^a_t defined as the value where $E^F_t = A(P^a_t) + Q^{NT}_t$

P^b_t defined as the value where $E^F_t = A(P^b_t)$

$$\Delta P^a_t = \frac{((P_t - k) + (P_t - P^a_t)) - |(P_t - k) - (P_t - P^a_t)|}{2}$$

$$\Delta P'^{a}_{t} = \frac{(\Delta P^{a}_{t} + 0) + \left|(\Delta P^{a}_{t} - 0)\right|}{2}$$

$$\Delta P^{b}_{t} = \frac{((P_t - k) + (P^{b}_{t} - k)) - \left|(P_t - k) - (P^{b}_{t} - k)\right|}{2}$$

$$\Delta P'^{b}_{t} = \frac{(\Delta P^{b}_{t} + 0) + \left|(\Delta P^{b}_{t} - 0)\right|}{2}$$

$$Return_t = C^{F}_{t\ NT} - C^{F}_{t\ R}$$

$$\chi_t = E^{F}_{t}.\Delta P'^{b}_{t}$$

$$\varepsilon_t = \int_{k}^{P_t - \Delta P'^{a}_{t}} A^{F}_{t}(P) + Q^{NT}_{t}\, dP\ + E^{F}_{t}.\Delta P'^{a}_{t}$$

$$\theta_t = (k - P_t).Q^{NT}_{t} + \int_{P'}^{P_t} A_t(P)dP - (A^{F}_{t} - Q^{NT}_{t}).(P_t - P')$$

where $P' = A^{F^{-1}}_{t}(A^{F}_{t} - Q^{NT}_{t})$

$$\varphi_t = \frac{(\theta_t + 0) + \left|\theta_t - 0\right|}{2}$$

$$Return_t = \frac{(\chi_t + \varepsilon_t) - \left|(\chi_t - \varepsilon_t)\right|}{2} - \int_{k}^{k+\Delta P'^{b}_{t}} A^{F}_{t}(P)dP + (E^{F}_{t}(P^{R}_{t} - P_t) - \int_{P_t}^{P^{R}_{t}} A^{F}_{t}(P)dP - I(Q^{NT}_{t+1}) - \varphi_t$$

$$OverallReturn = \sum_{t=1}^{t=3} \mathrm{Re}\,turn_t$$

<u>CCS amendment under tax</u>

$$Return_t = \frac{(\chi_t + \varepsilon_t) - \left|(\chi_t - \varepsilon_t)\right|}{2} - \int_{k}^{k+\Delta T'^{b}_{t}} A^{F}_{t}(T)dT + (E^{F}_{t}(T^{R}_{t} - T_t) - \int_{T_t}^{T^{R}_{t}} A^{F}_{t}(T)dT - I(Q^{NT}_{t})$$

<u>CCS amendment under cap and trade</u>

$$Return_t = \frac{(\chi_t + \varepsilon_t) - \left|(\chi_t - \varepsilon_t)\right|}{2} - \int_{k}^{k+\Delta P'^{b}_{t}} A^{F}_{t}(P)dP + (E^{F}_{t}(P^{R}_{t} - P_t) - \int_{P_t}^{P^{R}_{t}} A^{F}_{t}(P)dP - I(Q^{NT}_{t})$$

- ## Annex 3: Model Results

Biomass

Returns over investment	**Mean**	**Standard Deviation**	**Maximum**	**Minimum**	**Percentage of observations >=0**
Tax case 1	190.68	87.60	592.33	-101.29	99.4%
Tax case 2	668.53	92.02	1037.88	320.41	100%
Tax case 3	652.05	98.72	1050.69	343.62	1005
Cap and trade	657.28	872.81	6120.74	-1254.86	78.3%
Cap with floor	714.79	798.44	6120.74	-888.48	80.0%
Cap with ceiling	474.97	480.52	1753.44	-930.58	79.4%
Comparison of returns between instrument					
Cap over tax 1	466.60	865.23	5802.06	-1375.45	70.6%
Cap over tax 2	-9.92	826.70	6063.58	-1757.98	46.9%
Cap over tax 3	3.41	830.09	5982.54	-1764.48	48%
Cap with floor over tax 1	524.11	790.37	5802.06	-1008.89	71.4%
Cap with floor over tax 2	47.77	751.92	6063.58	-1410.7	47.3%
Cap with floor over tax 3	60.30	756.50	5982.54	-1443.34	48.0%
Cap with floor and ceiling over tax 1	283.93	469.77	1375.17	-1010.04	70.7%
Cap with floor and ceiling over tax 2	-194.82	437.09	909.23	-1410.07	40.8%
Cap with floor and ceiling over tax 3	-177.13	443.44	906.33	-1425.87	42.6%
Cap with floor over cap	57.51	152.07	682.44	-327.67	93.2%
Cap with floor and ceiling over cap	-187.42	515.54	677.79	-4639.51	61.2%

CCS

Returns to investment	**Mean**	**Standard Deviation**	**Maximum**	**Minimum**	**Percentage of observations ≥ 0**
Tax case 1	-615.54	90.36	-246.90	-854.32	0%
Tax case 2	-302.56	90.60	86.56	-603.26	0.01%
Tax case 3	-349.70	100.01	45.77	-639.29	0.01%
Cap and trade	-306.99	466.57	3198.87	-942.04	22.3%
Cap with floor	-305.79	464.12	3198.87	-941.96	22.3%
Cap with ceiling	-446.64	278.39	526.54	-942.03	5.6%
Comparison of returns between instrument					
Cap over tax 1	308.55	448.75	3618.77	-556.71	73.4%
Cap over tax 2	-8.77	421.81	3018.76	-838.52	42.6%
Cap over tax 3	40.72	428.18	3192.00	-813.07	47.9%
Cap with floor over tax 1	309.75	446.10	3618.77	-424.07	73.1%
Cap with floor over tax 2	-7.70	419.43	3018.76	-682.31	42.6%
Cap with floor over tax 3	41.96	425.56	3192.00	-665.81	47.9%
Cap with floor and ceiling over tax 1	169.86	255.41	884.19	-404.36	72.5%
Cap with floor and ceiling over tax 2	-142.57	237.28	553.87	-677.88	30.8%
Cap with floor and ceiling over tax 3	-95.56	241.70	595.34	-689.70	41.0%
Cap with floor over cap	1.20	28.01	183.38	-157.7	94.3%
Cap with floor and ceiling over cap	-137.33	269.32	186.49	-2758.39	61.7%